

STATISTICAL SUMMARY AND EVALUATION
ON ELECTRIC POWER GENERATION FROM WIND POWER STATIONS

Dimitri R. Stein

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STATISTICAL SUMMARY AND EVALUATION
ON ELECTRIC POWER GENERATION FROM WIND POWER STATIONS

Dimitri R. Stein*

Since the end of the war, the technical developments of wind power generation has made significant advances and wind power generation stations have already been operated for many years in many countries. Up to the present, only incomplete data is available on operation of such plants. In order to perform economic planning and for operation of wind power generation plants, it is necessary to know the magnitude of energy production as a function of the design, the operational condition and the wind conditions, on the uniformity of energy production, peak power generation, the period of zero wind which must be bridged, as well as the operational periods for average and design performance levels. The present paper attempts to evaluate the operational results of Danish wind power generation plants of various sizes and types which were operated in significant numbers between 1941 to 1944. Several designs are evaluated.

Energy Made Available by Wind Power Generation Plants

The power absorption of the wind wheel having a certain diameter in a free airstream can be determined theoretically** as well as experimentally*** as a function of the wind velocity.

*The present paper represents an excerpt of an investigation carried out by the author between 1945 and 1946 for the Berlin Electrical Works Association.

**See A. Betz, Wind Energy and Its Exploitation by Windmills Vandenhoeck & Ruprecht, Goettingen, 1926.

***See Seifert, Investigations of Wind Wheels. Results of the Aerodynamic Test Installation Goettingen, 13, p. 139 ff.

****Numbers in margin indicate pagination in original foreign text.

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Usually the magnitude and duration of wind velocities cannot be accurately determined for the planning of wind power generation plants. Therefore, there is a considerable uncertainty associated with the determination of the energy which a wind generation station could produce. Even if the wind conditions were sufficiently known, the energy output can only be approximately determined. The most important parameter, the useful energy, can however, usually be determined only within a wide range in most cases.

It is obvious that the ratio of incoming energy to useful energy will depend greatly on the type and method of operation of any wind generation station. It can only be described accurately under certain conditions. Practical operational results of energy production from a large number of wind power generation plants over an extended time period are especially important for German conditions, since over the last few years, several test installations of various types have been built. In this way, we can obtain basic information on the order of magnitude of the energy supply of wind power generation stations.

The data on the experience with these stations becomes especially important because of the many contradictions in the literature and material written by the manufacturers. Often the available energy is overstated and very often it is even set equal to the consumed energy. The economic analysis carried out on this basis will then, of course, not apply. Therefore, it is absolutely necessary to have data from experience on these stations for proper technical and economic analysis. In this connection, the following questions are important in the evaluation of operational results of wind power generation stations:

1. What is the energy production of a wind power generation station with certain dimensions?

TABLE 1
ENERGY PRODUCTION OF DANISH WIND POWER GENERATION STATIONS
1941 TO 1944

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	1941		1942		1943		1944	
	#	Production kWh	#	Production kWh	#	Production kWh	#	Production kWh
January	43	108.032	81	149.214	86	258.693	88	481.765
February	44	98.919	83	200.163	86	404.458	88	280.132
March	44	123.583	84	255.828	85	335.088	87	284.917
April	48	106.174	84	188.557	84	340.075	87	254.741
May	49	115.117	84	161.770	84	202.211	87	255.737
June	52	110.482	84	179.537	87	174.569	87	159.203
July	59	87.526	83	164.468	87	150.160	86	105.089
August	60	130.463	82	127.527	87	224.588	86	144.499
September	63	129.854	84	202.368	86	218.824	84	247.998
October	64	192.048	86	261.842	87	220.429	84	152.947
November	64	231.682	86	247.163	87	216.463	84	331.774
December	65	259.459	85	267.365	87	283.862	83	247.121
Yearly production kWh		1.780.200		2.470.767		3.223.239		3.013.491

a) How does the energy production depend on the operational characteristics?

b) How does the energy production depend on the wind conditions?

2. What fraction of the wind energy offered is exploited in practice?

3. What is the uniformity of energy production over short and long time periods?

4. What are the peak values?

5. What is the time duration of windless periods on the average?

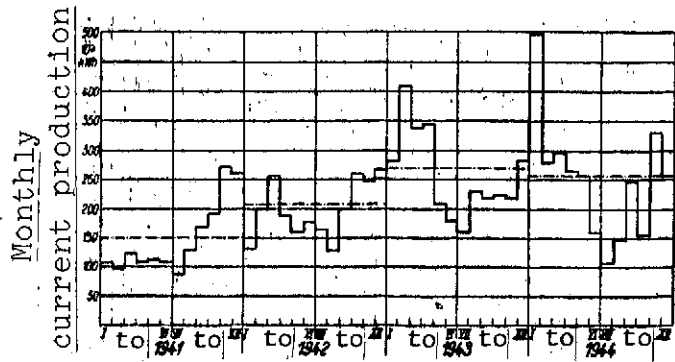


Figure 1. Energy production of Danish windmills.

6. How long is the average and design power delivered?

7. What is the dependence between energy production and wind wheel diameter?

Detailed specifications on energy production by wind power generation stations were difficult to collect in most European and non-European countries, because wind energy has only been exploited to a significant degree over the last few years, and up to the present, only a few installations have been built and operated. Denmark represents an exception to this, because between 1940 and 1942, the development of wind power generation increased drastically. The beginnings of this development have already been described,* so that in the following, we will only consider the operational results since 1940 on the large number of wind power generation stations.

* See D. R. Stein, "Importance and Advances in Wind Power Exploitation in Denmark", *Elektrizitätswirtschaft*, Vol. 41 (1942) pp. 346-349, p. 370-374 and p. 390-392, as well as "Wind Power Generation Stations in Denmark," paper by the Working Group "Wind Power Generation," 2nd edition, Berlin, 1944.

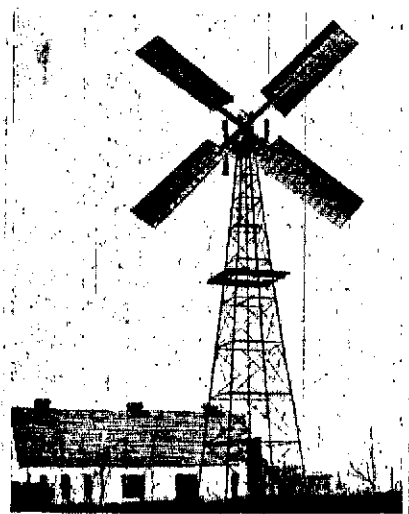


Figure 2. Foldable sail installation of the firm Lykkegaard (wind wheel diameter 18 m, power 30 kW at 10 m/sec).

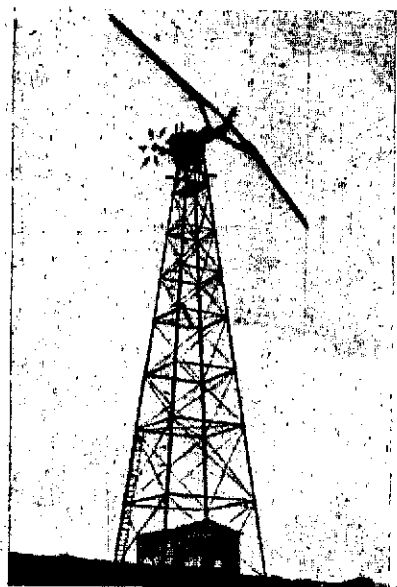


Figure 3. Fast unit of the firm F. L. Smidth (wind wheel diameter 17.5 m, power 50 kW at 11 m/sec).

Table 1 and Figure 1 give the numbers and energy production for the Danish wind power generation stations.* In 1944, there were 88 wind power generation stations having a wind wheel diameter of more than 12 m with a maximum energy production of 481,765 kWh (January, 1944). This compares with over 16 stations with a current supply of 27, 424 kWh (July, 1940).

Statistical Evaluation of the Energy Production

The current production by the wind power generation stations discussed covers two types of constructions. Also, the orders of magnitude are quite different. Most of the installations are so-called foldable sail installations ** (Figure 2) which were designed by the Danish professor La Cour and built by the firm

*See "Monthly Reports of the Association of Hydroelectric Plant Managers in Denmark", years 1940 to 1944.

**D. R. Stein, *ibid.*

Lykkegaard in Ferritslev on Fuenen. These installations were produced with wind wheel diameters between 12 and 18 m. They are /281 characterized by simple operation and safety. For this, one accepts a limited degree of exploiting the wind energy. Usually these devices cannot be operated in a purely automatic mode.

The second type of construction was built by the firm F. L. Smidth, Kopenhagen, in the years between 1939 and 1941. New aerodynamic and mechanical engineering methods were applied.* These types are delivered in two sizes, with 17.5 m and 24 m diameter of the wind wheel (Figure 3).

The Lykkegaard and the F. L. Smidth units usually use accumulator batteries to supply local direct current networks in small communities. Sometimes they are used as an energy source for individual agricultural and industrial units. Usually a diesel installation is available as a backup. The wind power generation plants are usually located close to the consumer at a windy location. Some installations, especially those of F. L. Smidth, operate in conjunction with large over-land networks. Some of these use convertors to supply three-phase current networks.

Lykkegaard Wind Power Generation Plants

In the years between 1941 and 1944, about sixty Lykkegaard wind power generation plants were operated. Most of these were units having a wind wheel diameter of 18 m. The others had wind wheel diameters of 16 m, 14 m, and 12 m. In order to evaluate the energy production, we will first investigate 21 installations in the 18 m version. For these, we already have operational results for the years 1940/1941.* We have, on purpose, summarized the results of large, medium sized, and small

* D. R. Stein. *ibid.*

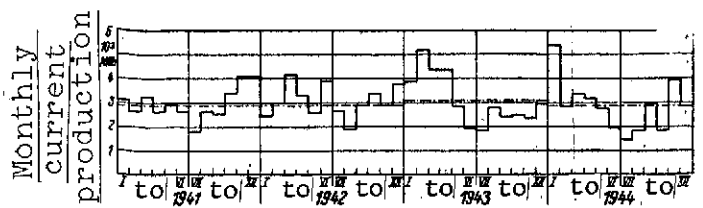
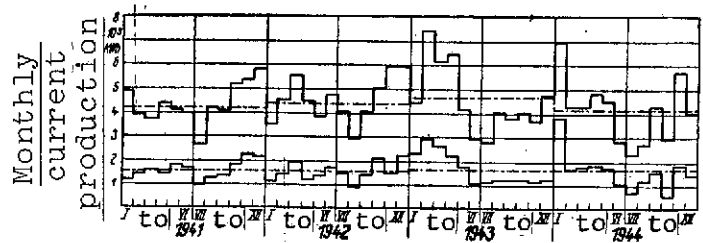


Figure 4. Average energy production of 21 Lykkegaard wind generation stations, wind wheel diameter 18 m.

Figure 5. Average energy production of four Lykkegaard wind generation stations, wind wheel diameter 18 m, with generated power above or below average levels, respectively.



energy levels, so as to obtain average values. When the data is analyzed for all of the installations having the same size, one obtains very similar results, as additional calculations showed. The wind power generation plants under consideration are distributed over all of Denmark, especially on the small islands where there are no large overland networks.

In the first place, we are interested in the numerical magnitude of the energy production on the average. The corresponding values for installations with the 18 m wind wheel diameter are shown in Figure 4 for the years 1941 to 1944. The yearly average values for all the installations are given by dashed lines, just like in Figure 1 and in the other figures.

As already mentioned, we are dealing with average production values, and good installations could considerably exceed them. In Figure 5, we show the data for the wind power generation stations at Askov, Besser Samsø, Kølstrup, and Lønborg, which have a considerably greater current production. We also show the results of installations with sub-average energy production, and we also show the values for Gjedsted, Nørager, Sønderø, and Sønder Omme in the same way.

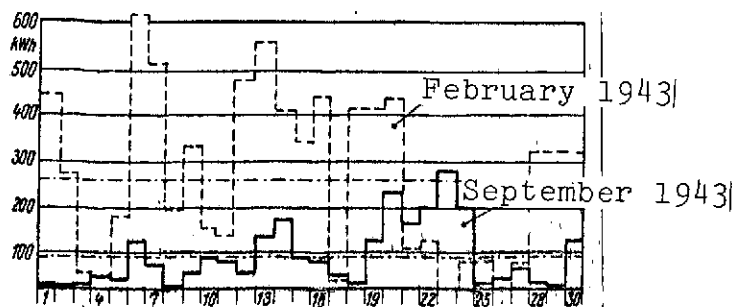
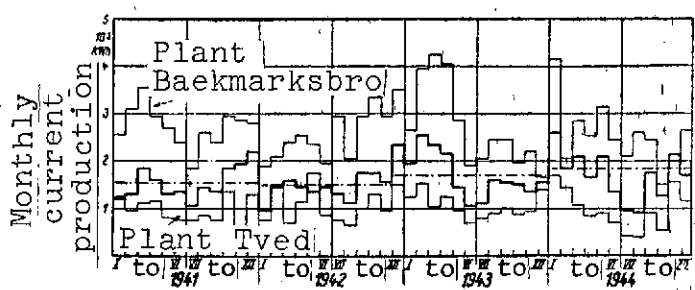


Figure 6. Daily energy production of the wind generation station Kølstrup for February and September of 1943.

Figure 7. Average energy production of 7 Lykkegaard generation plants, wind wheel diameter 16 m.



The figures shown up to the present do not show how the energy production of the wind power generation stations is distributed over the individual days. Figure 6 gives this data for a representative installation with above-average current production, the wind power generation station at Kølstrup at Odense on Fuenen (February and September, 1943).

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In order to obtain the complete results, we will also consider the production data from small wind power generation stations having wind wheel diameters of 16, 14, and 12 m. These installations are only used for supplying individual farms or rural plants. Figures 7 to 9 show the production results of these installations for the years 1941 to 1944.

F. L. Smidth Wind Power Generation Plants

The number of wind power generation plants made by this firm in operation amounted to 18 in the year 1944. Six of these had a wind wheel diameter of 24 m. Except for the USSR, these are the largest wind power generation plants built in Europe.

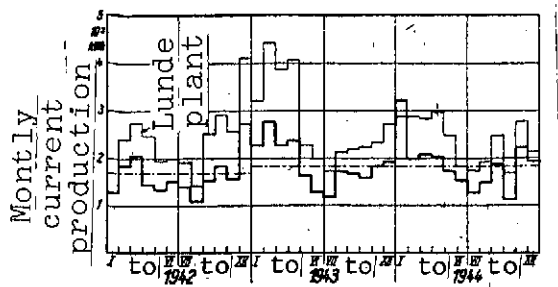
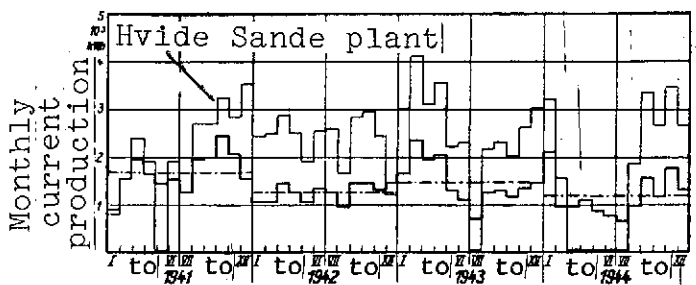


Figure 9. Average energy production of 4 (1941:2) Lykkegaard wind power generation stations, wind wheel diameter 12 m.

Figure 8. Average energy production of 3 Lykkegaard wind generation stations, wind wheel diameter 14 m.



In addition to this type, we also included 12 plants with a 17.5 m wind wheel diameter* in our investigations. The operational results of these plants designed according to modern analysis are, of course, very interesting. In spite of the small number of these installations, we can see a certain uniformity and this makes it possible to carry out a statistical data analysis and evaluation. Figures 10 and 11 show the results of the F. L. Smidth plants for the two types for average as well as sub-average energy production, in the same way as was done for the Lykkegaard installations.

Evaluation of Energy Production

The evaluation of the operational results for the wind power generation plants will be carried out as a sequel to the section "Energy Production" which discussed the questions mentioned above.

*In the case of these two plants, the wind wheel diameter was later on increased to 18.5 m.

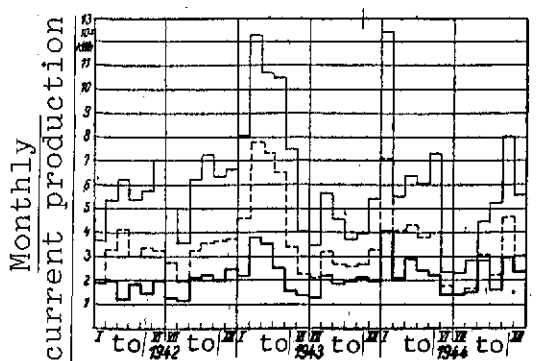
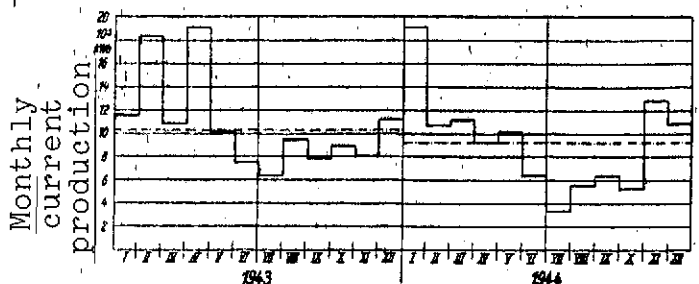


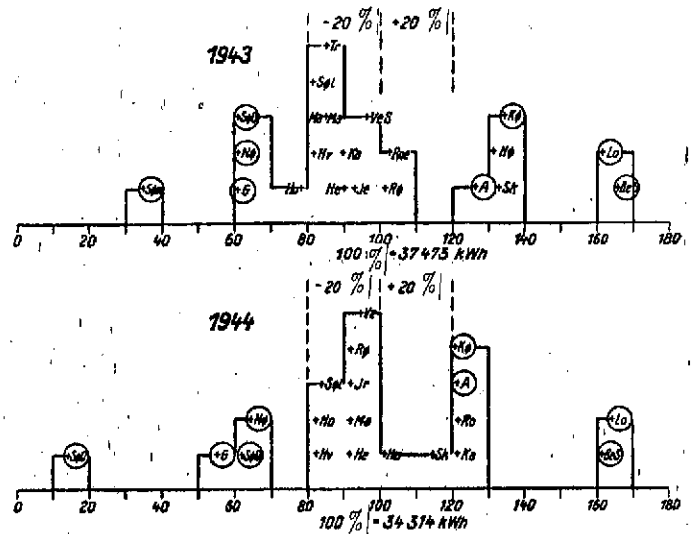
Figure 10. Average energy production of F. L. S. wind power generation stations, wind wheel diameter 17.5 m, with current production above, at, and under average levels.

Figure 11. Average energy production of 6 F. L. S. wind power generation stations, wind wheel diameter 24 m.



1. Absolute Magnitude of Energy Production of Wind Power Generation Plants

The figures showing the total production of all the installations (Figure 1), especially for the years 1943 and 1944, during which the number of wind power generation plants remained essentially constant, show the considerable fluctuation of the current produced as a function of the season. During the summer months, the energy production is at a minimum. In the other times, one can count on a uniform current production. During the winter months, the current production reaches peak values. These monthly peak values can considerably exceed the minimum production levels and even the average production levels to a considerable extent. We are primarily interested in investigating wind power generation plants of the same type, so as to draw general conclusions on the expected magnitude of energy production for individual wind power generation plants.



Each plant characterized by the first letters corresponds to a 1 cm². For clarification, the square is always indicated above the decade in which the percentage corresponding to this plant falls.

Figure 12. Percentage distribution of the average yearly production of 21 Lykkegaard wind power generation plants, wind wheel diameter 18 m.

In this connection, we will first discuss the Lykkegaard wind power generation plants. The figure showing the yearly production of 21 wind power generation plants with a diameter of 18 m for the years 1941 to 1944 (Figure 4) is especially important. As already mentioned, we intentionally selected plants with large, average, and low energy production for our analysis, so as to obtain a good average value. In order to evaluate the operational results, it is necessary to know the composition of the average values determined in this way. Figure 12 shows the yearly production of the individual plants depending on the energy production level for the years 1943 and 1944. As can be seen, the scatter is quite considerable. For example, of the 21 installations considered, on the average only 10 plants lie in a scatter range of $\pm 20\%$ of the average. One can also see that the individual plants deviate considerably upwards and downwards from the average value.

Under these conditions, is it at all permissible to formulate average values in the first place, or to use them for a general analysis? This question is especially important for the evaluation of the operational results presented above. This leads to the question of whether the fluctuations in energy production of the wind power generation plants under consideration are caused by the various geographic locations of the plants or if this is due to operational conditions. The answer is not easy to obtain. Of course, the local location of the individual plants is more or less favorable, so that there is a difference in wind available to the plants. The available wind on the Danish mainland is relatively uniform, it appears. Of course, there are favored locations (for example, Gjedser, Skagen, Samso Island) where especially good wind conditions have been produced by surrounding the ocean with land. /283

a) The method of operation

The most important reason for the considerable deviations in energy production of the same installations is caused by the differences in operational conditions. A large part of these plants supply small local direct current networks. During strong wind conditions and relatively small energy distribution, the accumulator batteries will soon be filled so that the operation will then have to be interrupted. In another group of users, which exclusively supply one user or an agricultural or industrial operation, these conditions are even intensified. In addition, we have the fact that the Lykkegaard installations were usually not operated at night, because most of the operators could not let the installations operate at night without surveillance. Another group of wind power generation plants considered works in parallel with a local direct current network which is very large or supplies three-phase networks through convertors, and for which the current produced can be immediately consumed.

Such installations can be operated almost continuously under adequate wind conditions and, therefore, transform almost all of the wind energy into electrical work.

The differences in operation mentioned above can therefore be categorized as follows:

1. Supply to individuals;
2. Supply of small local networks;
3. Parallel operation with large-scale direct current or three-phase overland networks.

In this way, we can understand the division into three groups when we consider the average yearly production as shown in Figure 12. Of course, there are changes and fluctuations within these groups as well. Nevertheless, the agreement of the individual plants according to their method of operation is quite good, as can be seen from a figure of energy production of the installations with over-average or sub-average current production (Figure 5). For the two groups which clearly deviate from the average value, i.e., for the individual installations and for the plants operating in parallel with large networks, it is possible to use percentages, such as for example, $\pm 45\%$, of the yearly production of the entire group and one finds that this applies for the individual years. The dependence of the production magnitude on operational conditions can also be seen from the fact that the influence of a change in wind conditions on energy production is always in the same direction during the individual months for the above average and below average plants considered. As a scale for a change in wind conditions, we can use the energy production of all of the 21 Lykkegaard wind power generation stations having the same design (Figure 4) to a good

degree of approximation. This is because the random irregular features in the installations will hardly have any effect.

Therefore, we find that it is permissible to form an average value of available operational results from a large number of wind power generation plants. The large scatter of the data from the installations can be based on differences in operational conditions, as mentioned above. This means that the average level of energy production during these four years is almost constant, both for the total number of wind power generation plants and for each of the individual generating plants having above average and below average production levels. The monthly fluctuations over the year are mostly equalized. These fluctuations are characterized by the ratio of average monthly maximum and minimum production ratio. In the following, these maxima and minima will be called yearly extreme values. Therefore, we have found that if the average wind conditions and operational conditions are known, it is possible to determine the actual energy production of wind power generation plants of a certain size within narrow limits. It therefore becomes possible to look upon the production data as experimental data for energy production of wind power generation plants, provided local wind conditions, operational characteristics, and efficiency are known.

In the Lykkegaard installations with a 16 m wind wheel diameter (Figure 7), it can be seen that the average value of the installations changes in the same direction as the fluctuations in wind conditions. The average values seem to be uncertain because of a small number of installations, which of course apparently also operate under different conditions. The other production values of an above average installation [Baekmarksbro] and of a below average plant (Tved at Svendborg) are distorted because of operational disturbances, which could very well have occurred in the distribution equipment. In

general, even these values follow the actual wind conditions. The characteristic ratio of average monthly maximum and minimum production, i.e., the yearly extreme value is 2.4 (1942) to 2.9 (1944).

In the case of the Lykkegaard wind power generation plants with the 14 m wind wheel diameter, we can note the very widely fluctuating energy production of the individual installations (Figure 8). We are talking about three plants. Apparently, this is based on the differences in operational conditions. This is especially clear from the uniform level of energy production of the plants Humlum and Lunde during the investigated years. The yearly extreme value fluctuates between 2.3 and 2.8 for the investigated years.

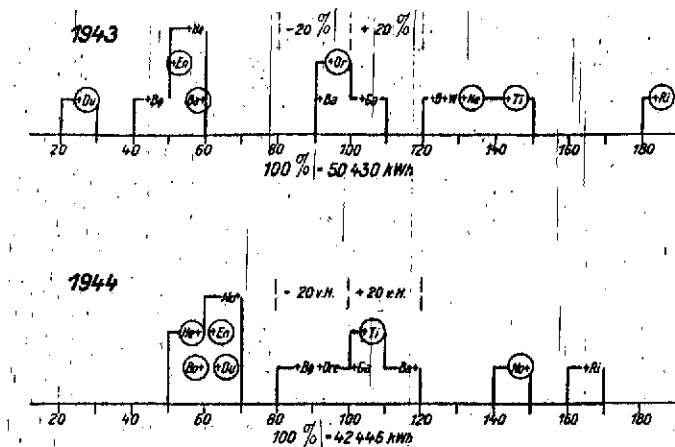
The 14 m and 16 m installation results show that the former probably produced more energy than the latter. The reason for this is probably the overdimensioning of the 16 m installations, which was done because no experience was available, compared to the actual energy requirement. This then leads to a poorer operation.

In the case of the Lykkegaard plants with a 12 m wind wheel diameter, the results for the individual plants are also not uniform. However, the average production data are relatively constant over the years investigated (Figure 9). In general, they change according to the wind conditions. The yearly extreme value fluctuates between 1.5 (1942) and 3.5 (1943). An installation with an above average production is shown separately in the figure.

In the F. L. Smidth wind power generation plants, we do not have as much numerical data as for the Lykkegaard installations, because these plants were only developed in 1940/41. At the beginning, there were of course certain difficulties. However, the uniform numerical data for the years 1943 and 1944 do show that these initial difficulties were mostly overcome, so that the operational results of the F. L. S. installations were evaluated according to our plans.

Most of the F. L. S. installations in operation have a wind wheel diameter of 17.5 meters. The dimensions are similar to those of the 18 m wind wheel diameter Lykkegaard installations. Therefore, we can make a comparison. The result of these F. L. S. plants are shown in Figure 10 for the years 1942 to 1944. The production values of the individual installations are very non-uniform and fluctuate greatly upwards and downwards from the average value. A percentage plot of energy production of the 12 installations is shown in Figure 13 for the years 1943 and 1944. The fluctuations are considerably greater than for the Lykkegaard values over the same time period. If we consider the energy production over the individual years, it is remarkable that the yearly energy production of the individual plants is quite uniform, so that again, we can make a division into operational groups just like we did for the Lykkegaard plants. /284

Figure 10 also shows the plants having above average and below average current production, depending on the different operational conditions. In this connection, we should note the increased average value of energy production of all of the investigated installations as compared with the Lykkegaard plants with a wind wheel diameter of 18 m. Also, one should note the high absolute value in production of individual F. L. S. plants (for example, Rindum, 1943; 92,870 kWh). The production of the F. L. S. installations with a diameter of 17.5 m is 29% higher



Each plant characterized by the first letters corresponds to a 1 cm². For clarification, the square is always indicated above the decade in which the percentage corresponding to this plant falls.

Figure 13. Percentage distribution of the average yearly production of 12 F. L. S. aeromotors, wind wheel diameter 17.5 m.

on the average for the investigated years than that of the Lykkegaard plants with a diameter of 18 m. For this comparison we use local supply conditions, and the F. L. S. installations are recalculated for a diameter of 18 m. These numbers prove that the F. L. S. plants exploit the wind much better than the Lykkegaard installations. Considering the larger losses in the Lykkegaard installations in the mechanical and electrical components, we can therefore assume that the exploitation of the free airstream ($c_1 \cdot \eta_{ges}$) is 0.30 for the F. L. S. plant and 0.20 for the Lykkegaard plants for a wind velocity of 6 m/sec. It is remarkable that the larger production of the F. L. S. plants occurs months with the increased wind velocity. The values for unfavorable wind conditions agree approximately for both manufacturers. The yearly extreme value of the F. L. S. plants is 5.1 (1944) at a maximum.

Of course, the operational results of the large F. L. S. plants with a 24 m wind wheel diameter (Figure 11) are most interesting. The first two such installations, Frederikshavn I and II, were operated starting at the beginning of 1942. At the end of 1943, already six such installations were operating and the current production was relatively uniform. The energy production for 1943 and 1944 shown in Figure 11 agrees for the most part with the changes in current production of the 18 m Lykkegaard wind power generation plants considered above. Here again it is remarkable that the wind conditions have a considerably greater effect on the F. L. S. installations than on the Lykkegaard wind power generation plants. This is even more true for plants with a wind wheel diameter of 24 m than for ones with a diameter of 17.5 m. The installations reach a monthly production level of 19,000 kWh (January, 1944) for high wind intensity, which corresponds to a continuous production of 35 kW. For a low wind intensity, it is 3200 kWh (July, 1944), which is equal to 6 kW continuous power output. The ratio of monthly high and minimum production reaches 5.9 for this case, and for the corresponding production of a Lykkegaard values with a 18 m wind wheel diameter and for the same months, the yearly extreme value is 3.7.

The differences in this ratio are produced because the F. L. S. installations exploit the higher wind velocities better /285 than the Lykkegaard plants, as was already established for the smaller F. L. S. installations. At the small wind velocities, they begin running only later on and they have the same or a smaller energy production than the Lykkegaard plants. The reason for this is the differences in construction between the F. L. S. and the Lykkegaard installations. The F. L. S. aeromotors are fast running machines with narrow blades, which only reach optimum values of the power coefficient at high wind velocities (7 to 9 m/sec). At small wind velocities, there is a relatively small exploitation of the wind.

TABLE 2.
USEFUL ENERGIES FROM DANISH WIND POWER GENERATION STATIONS
FOR THE YEARS 1941 TO 1944

Manufacturer	Wind wheel diameter	Operational mode*	Energy production in kWh				Average 1941 to 1944	Remarks
			1941	1942	1943	1944		
Lykkegaard, Ferritslev u/v - 3 to 4 4 blades	12	E	-	9,399	11,476	12,176	11,017	Agerso Plant data, 4 plants Hvide Sande
		O	16,271	14,995	17,358	14,252	15,719	
		U	25,036	28,288	32,381	-	28,569	
"	14	E	-	10,327	15,279	19,375	14,994	Sonder Bork data, 3 plants Humlum
		O	-	19,546	22,507	22,651	21,588	
		U	-	28,714	33,390	28,921	30,342	
"	16**	E	-	-	-	-	-	Baekmarksbro
		O	32,712	30,855	32,407	25,382	30,339	
		U	-	-	-	-	-	
"	18	E	18,973	18,678	20,469	19,450	19,393	data, 4 plants data, 21 plants data, 4 plants
		O	37,455	35,359	37,473	34,313	36,150	
		U	52,975	52,572	55,416	49,715	52,670	
F. L. Smidth, Copenhagen u/v = 7 to 9 2 blades	17.5	E	-	22,519	26,611	28,148	25,760	data, 4 plants data, 13 plants data, 3 plants
		O	-	39,427	50,430	42,445	44,101	
		U	-	69,408	80,190	69,668	73,122	
F. L. Smidth Copenhagen 8/v = 5 to 7 3 blades	24	E	-	-	-	-	-	data, 6 plants
		O	-	-	129,748	103,033	116,390	
		U	-	-	-	-	-	

* Operational mode: E = individual supply; O = local supply; U = parallel operation with overland network (see text).

** Not much generation data is available for this order of magnitude.

Based on this numerical data on energy production of wind power generation plants of various sizes of the two leading Danish firms, we can now answer the question of the effective level of energy production of a wind power generation plant having certain dimensions. The answer is given in Table 2. It is remarkable that the average production data of each plant agrees quite well for the individual years. The agreement supports the correctness of the numerical data and the method of investigation. It also emphasizes the result mentioned elsewhere that it is possible to predict the production output of wind power generation plants if average wind conditions, total efficiency, and operational procedure are known.

As can be seen, Table 2 considers the operational mode. The division into three basic operational states, as was already done when the production data was collected, for the supply of an individual user, supply of a small town, and parallel operation with an overland network, is characteristic of our method. It is obvious that if a small town is supplied or if we operate in parallel with a network, it is possible to exploit a larger fraction of the energy produced and if an individual user is supplied. The fact that the energy is consumed at the same time it is being produced plays a major role here. The conditions become more favorable as these times overlap. In other words, favorable operational conditions are produced when the load is uniform. However, the division into three categories is not binding, because very large exploitation values* can be obtained even when supplying individual users with small installations. This results in conditions which are the same as parallel operation with an overland network (Conclusion follows).

*See D. R. Stein. "New Wind Power Generation Plants for Supplying Agricultural Installations", Paper 8 of the Reichs Working Group "Wind Power," Berlin, 1945; and Rogge-Stein, New Electromechanical Wind Power Generation Plant, Elektrizitäts-wirtschaft, Vol. 42, 1943, pp. 348-363.

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